OPTIMIZATION OF TORQUE SENSOR INPUT PARAMETERS AND DETERMINATION OF SENSOR ERRORS AND UNCERTAINTIES

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Summary This paper introduces the basic knowledge about magnetoelastic torque sensor designed for non-contact measurements. The paper brings results of Institutional project "The development and realization of torque sensor with appropriate equipment." The optimization of torque sensor working conditions and sensor parameters are presented. The metrological parameters determined by testing showed availability of sensor using in outdoor applications. Another aim of the paper is evaluation of measurement uncertainty. It reviews the procedures currently applied for measurement uncertainty calculation according to ISO Guide.

1. INTRODUCTION

The monitoring and measuring of torque in civil engineering and manufacturing surroundings has to be accurate, reliable and economic. The outdoor applications of the torque sensors set special requirements concerning their long-term reliability in a wide temperature range as well as the wide measuring torque range. At present, very often used resistive torque gauge transducers provide high accurate measurements. But the main problem that limits the outdoor application of them is an unreliable operation or a failure in a high-humidity environment. Harmful effect on glue has limited their use in manufactory with aggressive environment. In addition, resistive torque gauge transducers are expensive and they require high maintenance levels. One of the low cost methods assumes using of magnetoelastic method in torque measurements [1, 2]. The main advantages of magnetoelastic sensors are: high sensitivity (depending on sensor core material), sufficient output voltage and output power, very high reliability, mechanical toughness and ability of multiple torque overloading (in comparison with resistive torque gauge transducers) [3]. Some shortcomings of magnetoelastic sensors are higher power consumption, ambiguity of transfer characteristic and sensor errors, e.g. hysteresis (property of sensor core material) and nonlinearity [4].

The main task of the project was to create a torque sensor including accessories from homemade materials, experimentally optimize working conditions and to determine metrological properties of the measurement set. The paper is divided into several chapters. Firstly, the magnetoelastic torque sensor principle and torque test equipment are described. Next chapter deals with optimization of input parameters. Finally, sensor errors and uncertainties in estimation of torque are computed.

2. TORQUE SENSOR PRINCIPLE

The magnetoelastic effect is the influence of the elastic stress on magnetization. The effect consists of a change in the magnetizing curve under a mechanical stress action. Magnetoelastic torque sensor consists of ferromagnetic cores, primary and secondary windings and a shaft.

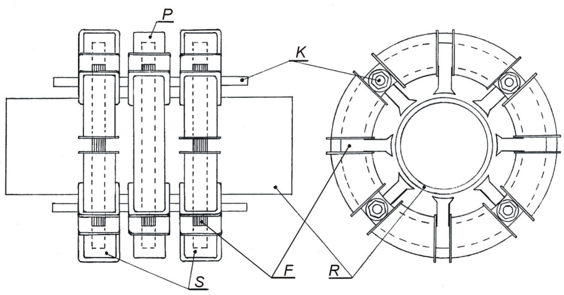

Fig. 1. Construction of magnetoelastic torque sensor EMTS-200Nm; P - primary windings, S - secondary windings, F - ferromagnetic core, R - shaft, K - screws

Magnetic field is generated by primary windings symmetric around excitation core (magnetic poles N and S). If no torque acts on the shaft, the magnetic fluxes of primary winding are mutually removed and secondary voltage is equal to zero. However, as torque is applied to the shaft, the magnetic field twists within the ring and field lines intersect with the surface of the ring in proportion to the amount of torque applied. Strain $+\sigma$ and stress $-\sigma$ are changed due to enlargement of twisting angle. Reluctances are changed (R_m is decreasing and R_m' is increasing) and secondary voltage is induced by magnetic flux change in coils marked A and B. The magnetoelastic torque sensor is depicted in Fig. 1 and an unroll coil system (circumferential) is depicted in Fig. 2.

The sensor works like a transformer with a variable coefficient of transformation. Under the action of external torque the output voltage changes. Torque test equipment is used in order to obtain sensor output characteristics and optimization of input parameters. It works on a principle of first kind lever, whose scheme is illustrated in Fig. 3.

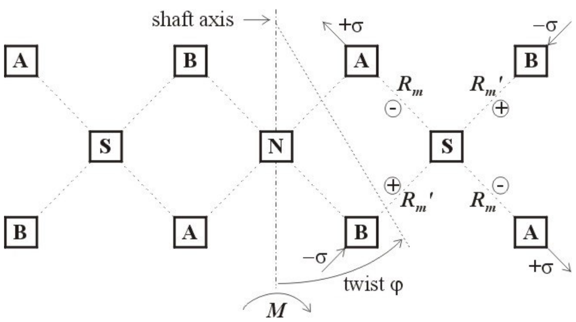

Fig. 2. Unroll coil system of the sensor

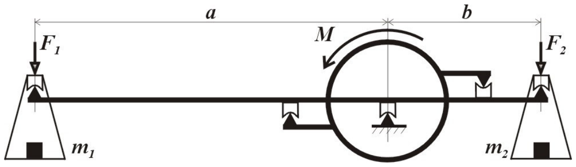

Fig. 3. Torque test equipment

Accurate weights are an input quantity transmitted from shorter lever arm onto the longer lever arm. Torque from the lever is transferred on the steel shaft by a double arm lever. The maximum reachable torque of the equipment is 279,6 Nm. The following equation is given for the transferred torque:

$$\begin{aligned} M &= (F_1 + \Delta m \cdot g)\cdot a - (F_2 - \Delta m \cdot g) = \\ &= F_1 \cdot a - F_2 \cdot b + \Delta m \cdot g \cdot (a+b) = \\ &= (a+b)\cdot g \cdot \Delta m \ , \end{aligned} \tag{1}$$

where Δm is weight displaced from one to other arm lever; F_1, F_2 are forces correspond to equilibrium lever state; a, b are lengths of relevant lever arms; g is gravitation constant. Substituting actual lever dimensions and parameters a = 1296 mm, b = 604 mm, g = 9,81 m.s^{-2}, we got relation:

$$M = 18{,}64 \cdot \Delta m \ \text{(Nm; kg)} \ . \tag{2}$$

3. OPTIMIZATION OF INPUT PARAMETERS

This chapter is divided into several subchapters. Firstly, sensor errors are defined because they are used in all the following paper parts. Optimization of input parameters is described in the next subchapters.

3.1 Sensor errors

Ones of criterions of sensor applicability are sensor errors. The standard IEC 60 770 [5], [6] defines inaccuracy, measured error, repeatability, hysteresis, and linearity. The errors are determined from five upscale and downscale full-range traverses ($n = 5$), measuring at twelve points in each the traverse. *Inaccuracy* is a characteristic of measurement process and it describes (lack of) accuracy. It is determined as the biggest positive and negative deviation of any measured value from an ideal value for increasing and decreasing inputs for any test cycle separately. *Measured error* is determined as the biggest positive or negative value of an ideal value from the average upscale errors and the average downscale errors. *Repeatability* is defined as the closeness of agreement among a number of consecutive output values measuring the same input value under the same operating conditions, approaching from the same direction. Usually measured as non-repeatability but expressed as repeatability. *Hysteresis* δ_{hys} is defined as the maximum difference in output for any given input (within the specified range) when the value is approached first with increasing and then with decreasing input signals (2). *Linearity error* δ_{lin} is defined as the maximum deviation of any points from a straight line drawn as a "best fit" through the calibration points of an instrument with a linear response curve (3). The errors are reported as a percentage of ideal output span.

$$\delta_{hys} = \left(\frac{\left| M'_{\downarrow} - M'_{\uparrow} \right|}{M_{\max} - M_{\min}} \right)_{\max} \tag{3}$$

$$\delta_{lin} = \left(\frac{M'_{ave} - M}{M_{\max} - M_{\min}} \right)_{\max} \tag{4}$$

$$M'_{ave} = \frac{1}{n} \sum_{i=1}^{n} \left(\frac{M'_{\uparrow}(i) + M'_{\downarrow}(i)}{2} \right) \tag{5}$$

In equations (3), (4) and (5), the symbols $M'_{\uparrow}$, $M'_{\downarrow}$, M'_{ave} and M are vectors with 12 elements, $M_{\max} = 205{,}04$ Nm , $M_{\min} = 0$ Nm .

3.2 Measuring apparatus

The set of measurements with the measuring apparatus (Fig. 4) was done in order to get optimal input parameters (frequency f of supply current and the current I_1). These parameters should be working parameters of torque sensor. So, the main criteria of determination these parameters are possibly the lowest linearity error δ_{lin} and hysteresis δ_{hys} .

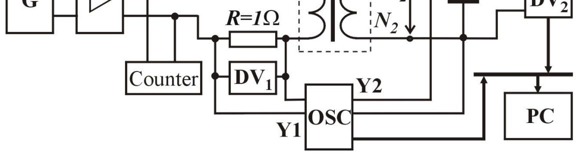

Fig. 4. Measuring apparatus connection; generator (G)*, amplifier* (▷)*, torque sensor* (S)*, resistance R =1Ω, digital voltmeters* (DV_1 *and* DV_2)*, oscilloscope* (OSC)

The output sensor voltage is shown in Fig. 5a. A capacitor (C) is used because of a suppression of non-harmonic distortion of the output voltage. The usage of the capacitor enables to compensate high order harmonics of the voltage, Fig. 5b. Output sensor voltage is measured by accurate voltmeter (DV_2) and transferred to personal computer (PC) via RS232. The frequency of the supply current is measured by frequency counter (Counter). The hysteresis curve in Fig. 5c can be observed by using the measuring apparatus described above.

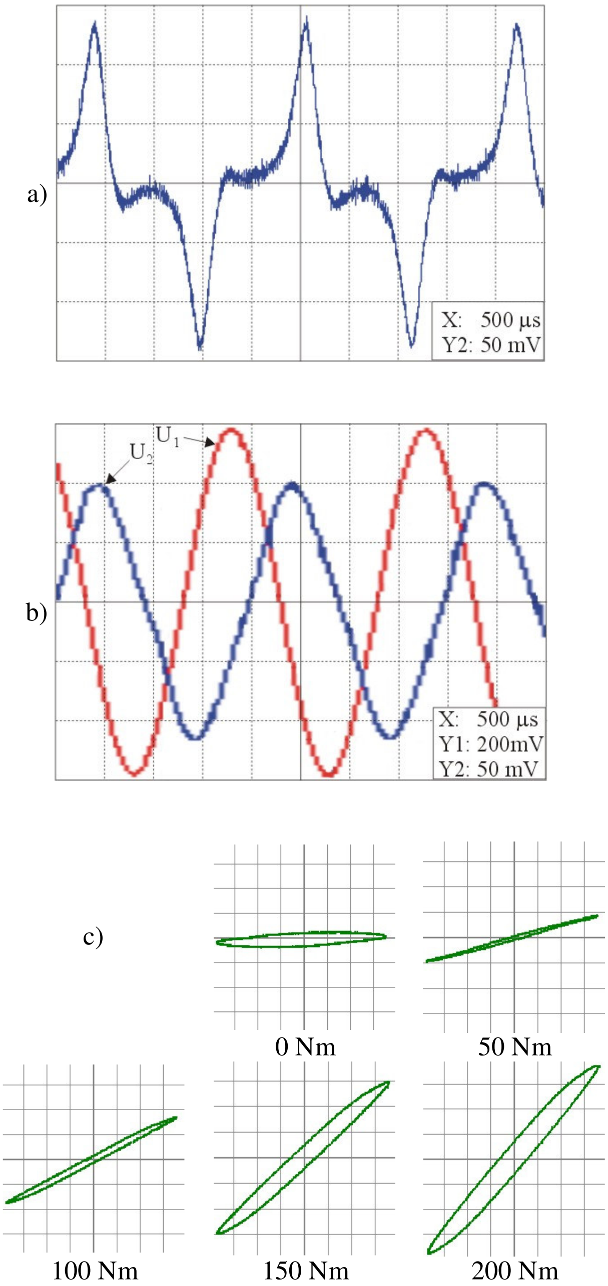

Fig. 5. Output sensor characteristics a) $U_2=f(t)$ (C is not connected), b) $U_2=f(t)$, connection with capacitor C, c) effect of torque loading on hysteresis curve

3.3 Determination of frequency

Determination of optimal frequency of supply current is the first step of input parameters optimization [4]. Influence of frequency on torque sensor was tested at $M = 0\,\text{Nm}$ and $M = 205{,}04\,\text{Nm}$. It is shown in Fig. 6a, $U_2 = f(\text{f})\big|_{M=0\text{Nm}}$ and $U_2 = f(\text{f})\big|_{M=205{,}04\text{Nm}}$.

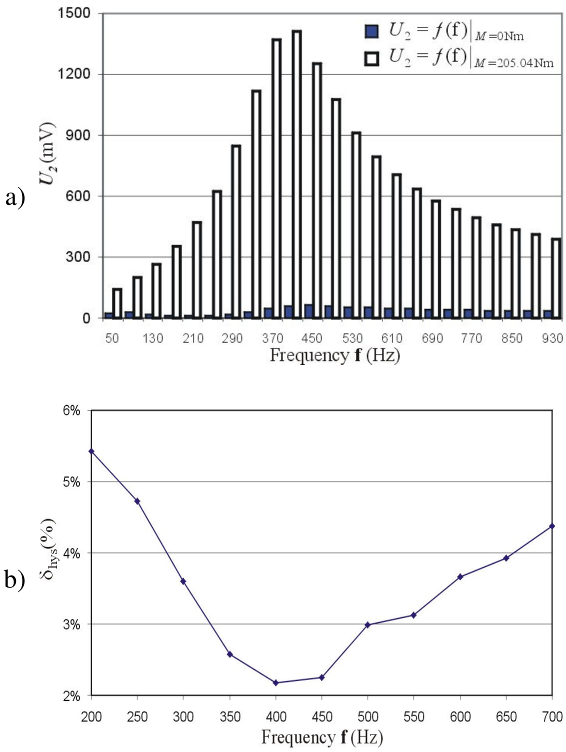

Fig. 6. a) Influence of frequency on torque sensor, b) dependency of hysteresis error from frequency

From the point of view of maximal gain and minimal offset the optimal frequency appears around 400 Hz. Fig. 6b shows dependency of hysteresis error from frequency f for supply current $I_1 = 0{,}3\text{A}$, $\delta_{hys} = f(\text{f})\big|_{I_1=0{,}3\text{A}}$. The hysteresis increases for high frequencies. So, the optimal frequency $\text{f} = 400\text{Hz}$ is determined for other experiments.

3.4 Determination of supply current

The second step is determination of optimal supply current I_1 [4]. Output characteristics $U_2 = f(M)$ for various values of I_1 were measured, see Fig. 7a. Considering criteria of the optimal input parameters determination (mentioned above), the characteristic with effective supply current 0,50 A reaches the smallest linearity error and hysteresis error. Dependency of hysteresis error and linearity error from supply current is shown in Fig. 7b.

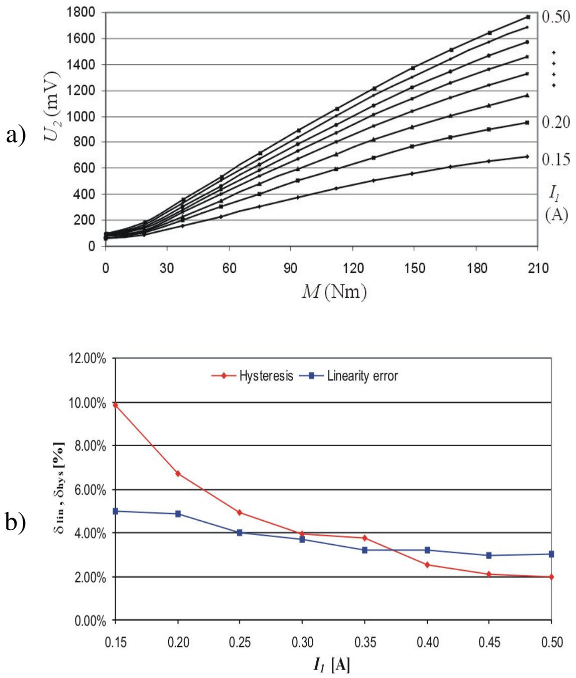

Fig. 7. a) Output characteristics of torque sensor for various values of I_1, b) dependency of hysteresis error and linearity error from supply current

3.5 Output sensor characteristic

The measured characteristic of output sensor voltage $U_{2\uparrow}$ (if torque M is increasing from 0 Nm to 205,04 Nm – characteristic upward) and $U_{2\downarrow}$ (if torque M is decreasing from 205,04 Nm to 0 Nm – characteristic downward) are shown in Fig. 8. In order to output voltage conversion U_2 into measured torque a static transfer characteristic is determined as a straight line and calculated by the least square method. Torque M' corresponding to sensor output voltage U_2 can be calculated from linear output characteristic $U_{2lin} = -6{,}0726 \cdot M + 1658{,}21$ as:

$$M' = -\frac{U_2 - 1658{,}21}{6{,}0726} \tag{6}$$

Eventually, $M'_{\uparrow}$ can be calculated by substituting $U_{2\uparrow}$ into (5), accordingly $M'_{\downarrow}$ by substituting $U_{2\downarrow}$.

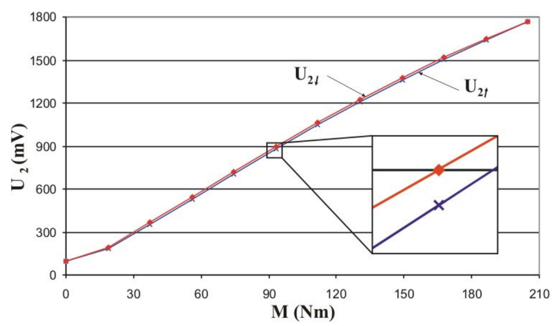

Fig. 8. Measured characteristic of output sensor voltage (U_2=f(F))

4. DETERMINATION OF ERRORS AND UNCERTAINTIES

Dependency of minimal differences ($ZO_{\min}$) and dependency of maximal differences ($ZO_{\max}$) from input quantity are depicted in Fig. 9. Difference between output average characteristic and straight line (calculated by the least square method) is labeled as ZPL. These characteristics are reported as a percentage of ideal output span. Inaccuracy can be determined as a maximum of characteristic $ZO_{\max}$ and minimum of $ZO_{\min}$. Similarly, linearity error can be determined as maximum of characteristic ZPL.

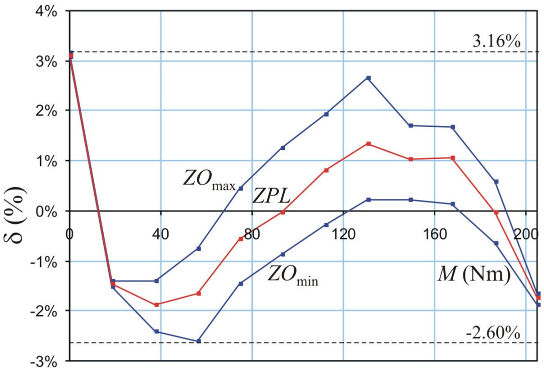

Fig. 9. Sensor error characteristics (δ=f(F))

This nonstandard representation by metrological characteristics ($ZO_{\min}$, $ZO_{\max}$, ZPL) is closely associated with uncertainty of measurement. The characteristics are more suitable for errors representation.

Following the previous definitions, the sensor errors are computed in Tab. 1.

Tab. 1 Sensor errors

sensor error	label	value
Inaccuracy	δ_{ina}	-2,60 % ; 3,16 %
Measured error	δ_{me}	3,14 %
Repeatability	δ_{rep}	1,13 %
Hysteresis	δ_{hys}	2,18 %
Linearity	δ_{lin}	3,11 %

Modern measurement theory and practice assume getting a measurement result along with some characteristics of its uncertainty. The uncertainty of the measurement result reflects the lack of exact knowledge of the specified measurand. The ISO Guide [7] defines uncertainty (in Section D.5.2) as an expression of the fact that, for a given measurand and a given result of measurement of it, there is not one value but an infinite number of values dispersed about the result that are consistent with all of the observations and data and one's knowledge of the physical world, and with varying degrees of credibility attributed to the measurand. The Guide assumes that the evaluation of all uncertainty components is based on probability distributions characterized by variances. The variances are either estimated from a series of repeated observations (type A) or assumed to exist and estimated from available knowledge (type B).

$$\mathrm{E}(\alpha)^2 = \mathrm{E}(\beta)^2 = \left(\frac{\Delta_{\alpha \max}}{\sqrt{3}}\right)^2 = \\ = \left(\frac{0,0005}{\sqrt{3}}\right)^2 = 8,33 \cdot 10^{-8} \qquad (13)$$

The type B evaluation of standard uncertainty is

$$\xi = \theta + \eta + \tau + \rho \ , \qquad (7)$$

usually based on scientific judgment using all of the relevant information available [7].

Let's have a theoretical model of measurement $Y = \theta$, where Y is accurate torque. The result of a measurement y (output estimate) is realization of random variable ξ:

where η is random variable representing systematic

$$u = \sqrt{\mathrm{D}(\xi)} = \sqrt{\mathrm{E}(\xi - Y)^2} \qquad (8)$$

error and random error of the system, τ is random

$$u = \sqrt{\mathrm{E}(\eta)^2 + \mathrm{E}(\tau)^2 + \mathrm{E}(\rho)^2} \ , \qquad (9)$$

variable representing error of test equipment a ρ is random variable representing rounding error.

The uncertainty of measurement u characterizes the dispersion (D) of the values that could reasonably be attributed to the measurand:

$$\mathrm{E}(\rho)^2 = \left(\frac{\Delta_{\rho \max}}{\sqrt{3}}\right)^2 = \left(\frac{0,005}{\sqrt{3}}\right)^2 = 8,33 \cdot 10^{-6} \qquad (10)$$

After modification:

where $\mathrm{E}(\eta)^2$ is dispersion of η, $\mathrm{E}(\tau)^2$ is

$$\mathrm{E}(\eta)^2 = \left(\frac{\Delta_{ina}}{k}\right)^2 = \frac{(a_+ - a_-)^2}{12} = \\ = \frac{1}{12} \cdot \left(\frac{(\delta_{ina+} - \delta_{ina-})\, FS}{100}\right)^2 = 11,62 \qquad (11)$$

dispersion of τ, $\mathrm{E}(\rho)^2$ is dispersion of ρ.

Dispersion of rounding (2 significant digits) is determined by following relation:

Dispersion of η is determined by standard relation ($k = \sqrt{3}$ for rectangular probability distribution):

where FS is full scale (205,04 Nm).

$$M_e = M + \tau = (a_e + b_e) \cdot g_e \cdot \Delta m_e = \\ = \left((a + \alpha) + (b + \beta)\right) \cdot (g + \gamma) \cdot (\Delta m + \upsilon) \qquad (12)$$

Determination of $\mathrm{E}(\tau)^2$ is more complicated. Ideal value of test equipment is given by relation (1). Quantities a, b, g and Δm are affected by errors, so quantities a_e, b_e, g_e and Δm_e. The true value of test equipment can be formulated:

where α and β are random variables representing length measuring error of relevant lever arm a respectively b, γ is random variable representing error of gravitation constant (g) determination and υ is random variable representing error of weight (Δm). We assume rectangular probability distribution with mean value $\mathrm{E}(\alpha) = \mathrm{E}(\beta) = \mathrm{E}(\gamma) = \mathrm{E}(\upsilon) = 0$ for all the random variables. Dispersions are computed:

Random variables α, β, γ and υ are uncorrelated.

$$\mathrm{E}(\gamma)^2 = \left(\frac{\Delta_{\gamma \max}}{\sqrt{3}}\right)^2 = \left(\frac{0,005}{\sqrt{3}}\right)^2 = 8,33 \cdot 10^{-6} \qquad (14)$$

$$\mathrm{E}(\upsilon)^2 = \left(\frac{\delta_\upsilon}{\sqrt{3}} \cdot \frac{\Delta m_e}{100}\right)^2 = \left(\frac{0,5}{\sqrt{3}} \cdot \frac{\Delta m_e}{100}\right)^2 = \\ = \Delta m_e{}^2 \cdot 8,33 \cdot 10^{-6} \qquad (15)$$

Then dispersion of random variable τ can be stated by following formula:

$$\mathrm{E}(\tau)^2 = \left(\frac{\partial M_e}{\partial a_e}\right)^2 \cdot \mathrm{E}(\alpha)^2 + \left(\frac{\partial M_e}{\partial b_e}\right)^2 \cdot \mathrm{E}(\beta)^2 + \\ + \left(\frac{\partial M_e}{\partial g_e}\right)^2 \cdot \mathrm{E}(\gamma)^2 + \left(\frac{\partial M_e}{\partial \Delta m_e}\right)^2 \cdot \mathrm{E}(\upsilon)^2 \qquad (16)$$

$$\mathrm{E}(\tau)^2 = (\Delta m_e g_e)^2 \cdot \mathrm{E}(\alpha)^2 + (\Delta m_e g_e)^2 \cdot \mathrm{E}(\beta)^2 + \\ + \left(\Delta m_e (a_e + b_e)\right)^2 \cdot \mathrm{E}(\gamma)^2 + \\ + \left(g_e (a_e + b_e)\right)^2 \cdot \mathrm{E}(\upsilon)^2 = \Delta m_e{}^2 \cdot 2,94 \cdot 10^{-3} \qquad (17)$$

Giving (10), (11) and (17) into (9) we got the uncertainty of measurement which depends on Δm_e:

$$u = \sqrt{\mathrm{E}(\eta)^2 + \mathrm{E}(\tau)^2 + \mathrm{E}(\rho)^2} = \\ = \sqrt{2,94 \cdot 10^{-3} \cdot \Delta m_e{}^2 + 11,62} \qquad (18)$$

where Δm_e is loaded weight. Uncertainty characteristic of the torque measurement is in Fig. 10.

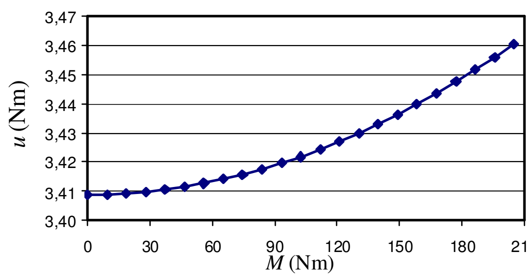

Fig. 10. Uncertainty characteristic of the torque measurement

The result of measurement M_{res} is given by:

$$M_{res} = M' \pm u \ \ (\mathrm{Nm}) \ , \qquad (19)$$

where M' is computed from U_2 (gained from measuring system) and u represents appropriate uncertainty of the system.

5. CONCLUSION

We have developed a magnetoelastic torque sensor for non-contact measurement. The sensor is designed from homemade materials and made at the Department of theoretical. electrotechnics and electrical measurement, labeled EMTS-200Nm. The sensor can be used in outdoor applications or in various fields of industry.

Optimal input parameters are experimentally determined (supply current I_1 = 0,5 A, frequency f = 400 Hz). Sensor errors are computed in Tab. 1. The sensor with appropriate apparatus can be used for measuring of nominal torque 200 Nm with safe overloading 150 % of full scale output. The output sensor voltage is 95 - 1765 mV.

Actually, a modified magnetoelastic torque sensor may be used in various growing applications – monitoring of motors, engines or monitoring of machine tool efficiency. Magnetoelastic torque sensors can be integrated directly into machines to monitor efficiency in real time. One of their primary engineering applications has been in the electronic control of power steering systems and automatic transmissions for the automotive industry.

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REFERENCES

[1] Garshelis, I. J., Whitney, K., May, L.: Development of a Non-Contact Torque Transducer for Electric Power Steering Systems. SAE Paper No. 920707, 1992.

[2] Garshelis, I. J., Aleksonis, J. A., Jones C. A., Rotay, R. M.: Development of a Magnetoelastic Torque Transducer for Automotive Transmission Applications. SAE Paper No. 970605, 1997.

[3] Jaroševič, A.: Magnetoelastic Method of Stress Measurement in Steel. In: Smart Structures, Kluwer Academic Publishers, NATO Science Series, 3/65, 1998, pp. 107-114.

[4] Mojžiš, M., Vojtko, J., Orendáč, M., Hodulíková, A.: Torque Sensor based on Villar's phenomena. In: Acta Electrotechnica et Informatica, vol. 4, no. 3, 2004, pp. 27-30.

[5] IEC 60770, Transmitters for use in industrial-process control systems - Part 1: Methods for performance evaluation, 1999-02. Part 2: Methods for inspection and routine testing. Part 3: Methods for inspection and routine testing, 2003-01.

[6] IEC 61298-2, Process measurement and control devices - General methods and procedures for evaluating performance - Part 2: Tests under reference conditions, 1995-07.

[7] Guide to the Expression of Uncertainty in Measurement. BIPM - IEC - ISO - OIML, 1995.